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Impact of Residual Soil Nitrate on In-Season Nitrogen Applications to Irrigated Corn Based on Remotely Sensed Assessments of Crop Nitrogen Status

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Abstract. Spatial and temporal variability of soil nitrogen (N) supply together with temporal variability of plant N demand make conventional N management difficult. This study was conducted to determine the impact of residual soil nitrate-N (NO_3-N) on ground-based remote sensing management of in-season N fertilizer applications for commercial center-pivot irrigated corn (*Zea mays* L.) in northeast Colorado. Wedge-shaped areas were established to facilitate fertigation with the center pivot in two areas of the field that had significantly different amounts of residual soil NO_3-N in the soil profile. One in-season fertigation (48 kg N ha^{-1}) was required in the Bijou loamy sand soil with high residual NO_3-N versus three in-season fertigations totaling 102 kg N ha^{-1} in the Valentine fine sand soil with low residual NO_3-N. The farmer applied five fertigations to the field between the wedges for a total in-season N application of 214 kg N ha^{-1}. Nitrogen input was reduced by 78% and 52%, respectively, in these two areas compared to the farmer's traditional practice without any reductions in corn yield. The ground-based remote sensing management of in-season applied N increased N use efficiency and significantly reduced residual soil NO_3-N (0–1.5 m depth) in the loamy sand soil area. Applying fertilizer N as needed by the crop and where needed in a field may reduce N inputs compared to traditional farmer accepted practices and improve in-season N management.

Keywords: residual soil nitrogen, in-season N management, remote sensing, N Reflectance Index, irrigated corn

Introduction

Research has shown that spatial variability in soil properties, nitrogen (N) dynamics, nitrate (NO_3) leaching potential, and plant sap NO_3 concentrations across fields and landscapes affect plant N status and crop productivity (Delgado, 1999; King *et al.*, 1999). Delgado (1999, 2001) reported that the spatial variability of residual soil NO_3-N in commercial operations of small grain, vegetable, and potato production was field specific and highly significant within a field, e.g., 100–225 kg ha^{-1} of residual

NO_3-N were found in different parts of a field subjected to uniform management. Although this variability could be assessed, farmers continue to manage their fields uniformly because they lack the technology and knowledge to manage within-field variability. Unfortunately, uniform field applications of N based on a few random measurements of soil NO_3-N result in parts of fields being over-fertilized and parts being under-fertilized with N.

Grid-based sampling systems have been used to better define soil N variability but the sampling is time-consuming and cost-prohibitive (Gotway *et al*., 1996). Khosla *et al*. (2002) investigated the potential of site-specific management zones (SSMZ) to improve N management in precision agriculture. The SSMZ treatments were able to take advantage of in-field nutrient variability better than conventional treatments consisting of uniform N rates based on yield goal N applications. Site-specific management zone treatments were simpler to implement and more cost-effective compared to a grid-based system. Ferguson *et al*. (2002) implemented an existing uniform N recommendation algorithm for site-specific N management to address spatial variability. Their results showed no consistent benefit in terms of yield improvement or reduced soil residual NO_3-N. They concluded that the algorithm was not sensitive enough to local differences in soil N supply and crop N demand within fields for variable rate N application to be of benefit. Parameters such as soil N supply and crop N demand that have high spatial and temporal dependence make site specific management difficult and may require an intervention rather than a preventative management strategy (Pierce and Nowak, 1999). Because of such spatial and temporal variability, Ferguson *et al*. (2002) suggested that strategies based on detecting crop N status and meeting crop N requirements with carefully timed fertilizer applications may ultimately improve N-use efficiencies.

During the past decade, considerable research has been conducted to investigate the use of remote sensing for assessing plant N status (Bausch and Duke, 1996; Blackmer *et al*., 1996; Schepers *et al*., 1996; Daughtry *et al*., 2000; Haboudane *et al*., 2002; Kostrzewski *et al*., 2002) and for recommending N fertilizer applications (Solie *et al*., 2000; Scharf *et al*., 2002; Bausch and Delgado, 2003). Advantages of using remote sensing for N management are spatial detail of the information collected and speed of collection. A disadvantage is weather, e.g., clouds. Even with this disadvantage, remote sensing may still be the best tool for understanding and responding to effects associated with spatial variability in soil N supply. Consequently, considerable effort is still required to develop N management systems and decision algorithms that are reliable and robust enough to justify adoption by producers.

The N Reflectance Index (NRI) presented by Bausch and Duke (1996) has been evaluated by Bausch and Diker (2001) and Bausch and Delgado (2003) for assessing plant N status in field size plots and for recommending in-season N applications in commercial irrigated corn fields. The objective of this study was to determine what impact differences in soil residual NO_3-N had on in-season N fertilizer applications to irrigated corn using ground-based remote sensing and the NRI to monitor and assess plant N status.

Materials and methods

This study was conducted in a commercial corn field in northeastern Colorado, USA during the 2001-growing season as part of a long-term (1997–2002), interdisciplinary precision farming project. The field was approximately 70 ha in area, contained sandy soils, had considerable topographic relief and was irrigated with a center-pivot sprinkler. Major soils in the field were classified as Bijou loamy sand (Coarse-loamy, mixed, superactive, mesic Ustic Haplargids), Dwyer fine sand (Mixed, mesic Ustic Torripsamments), and Valentine fine sand (Mixed, mesic Typic Ustipsamments).

This field was cropped with corn from 1997 to 2001 with crop rows parallel to the pivot road (field access to the irrigation systems' pivot point). The cooperating farmer managed all farming operations for crop production and applied sufficient inputs to minimize risk of yield loss. The whole field was uniformly managed in 1997 and 1998. In 1999 and thereafter, the northwest half had various N treatments applied in strips across the field; however, the southeast half remained under uniform management by the farmer except for a small area in the Valentine soil series as reported by Bausch and Delgado (2003).

Two areas of the field were selected as study sites based on differences in soil texture and soil profile residual NO_3-N. These areas are shown in Figure 1 as truncated wedges. The wedge-shape was selected to facilitate fertigation with the center pivot sprinkler system. Wedge A was located in the Bijou soil series (averaged 65% sand and 19% clay in the top 1.5 m of the soil profile) and wedge B in the Valentine soil series (averaged 92% sand and 6% clay in the top 1.5 m). The wedges were truncated between the sixth and ninth towers to better represent the two soil series and for the wedges to have identical areas (2.8 ha) on each soil type. Wedge B was the study area location reported by Bausch and Delgado (2003). Portions of these two field areas that contained wedge A and wedge B had been classified as high and low productivity zones, respectively, based on soil color determined from aerial photographs, topography and the farmer's past management experience (Fleming *et al.*, 2000).

Numbered symbols (dotted circles) within each truncated wedge (Figure 1) denote sampling locations for soil profile NO_3-N. Soil samples were taken on 5 April (Spring) prior to any N fertilizer application and on 11 October (Fall) after crop maturity. The samples were taken to a depth of 3 m in 300 mm increments using a hydraulic soil sampler. Two soil cores were taken at each sampling location approximately 300 mm apart and composited for each depth at each sample location. In the fall, one core was centered between the corn rows and the other was near the corn row. The soil samples were air-dried, ground and stored in sealed plastic bags. Two subsamples (20 g) from each sample were prepared for chemical analysis by extracting with 100 ml of 2M KCl, shaking for 1 h and filtering the liquid fraction. The extracts were analyzed for NO_3-N and NH_4–N using a Technicon[1] auto analyzer (Technicon Industrial Systems, Elmsford, NY, USA).

Tillage practices consisted of disking and ripping. A preplant liquid fertilizer mix (6 kg N ha^{-1}, 17 kg P ha^{-1}, and 56 kg K ha^{-1}) was applied to the soil surface on 25 April and incorporated with a second disking for seedbed preparation. Corn

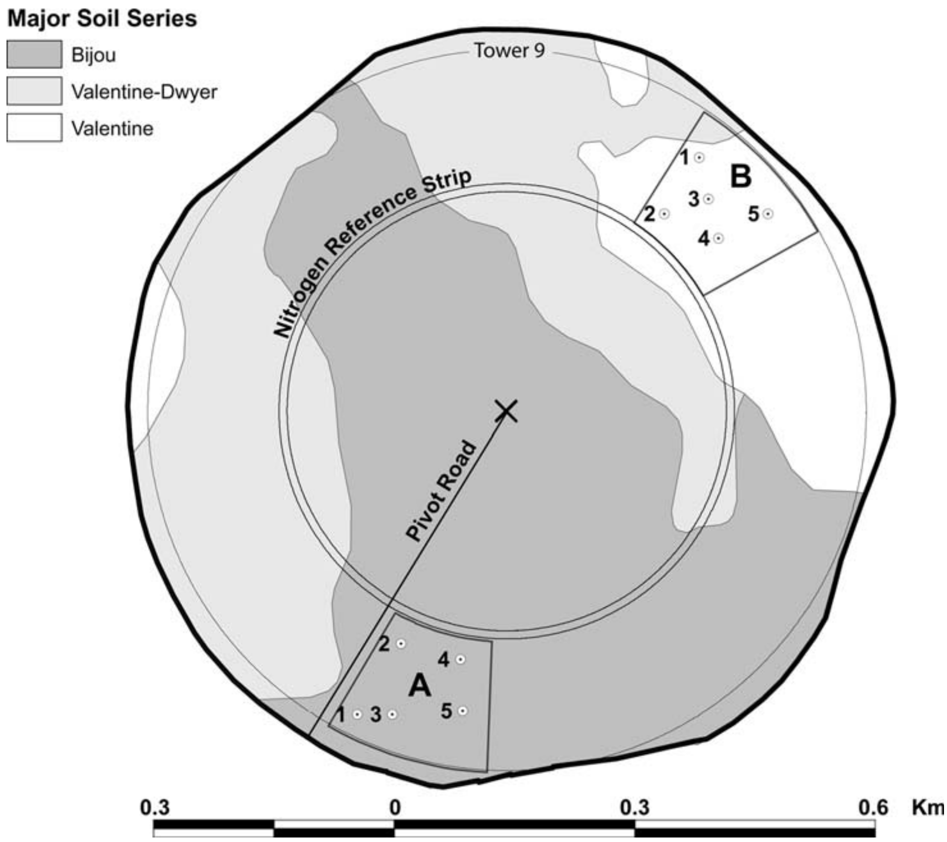

Figure 1. Commercial center pivot irrigated corn field showing major soils, location of truncated wedges, soil sample locations, and enriched nitrogen reference strip.

"Pioneer 34G81" (planophyle canopy) was planted on 15 May at 83,000 seeds ha^{-1}. A liquid fertilizer solution consisting of 28 kg N ha^{-1}, 34 kg P ha^{-1}, 6 kg S ha^{-1}, and 1 kg Zn ha^{-1} was applied to the side and below the seeds at planting. As previously stated, row direction was parallel to the pivot road, i.e., 32° from north. Row spacing was 0.76 m.

The USDA-ARS Water Management Research Unit in Fort Collins, CO provided the farmer with weekly irrigation schedules based on estimated crop evapotranspiration using SCHED, the USDA-ARS irrigation scheduling computer program (Buchleiter, 1995). However, the farmer made the final decision as when to irrigate and how much to apply. A total of 599 mm of irrigation water was applied in 25 irrigations. Well water samples were collected from 25 June to 28 August to determine NO_3-N in the ground water.

Timing of additional N (urea ammonium nitrate, UAN, 32% N) applied to the wedge areas during the growing season via fertigation was based on the NRI calculated from green and near-infrared (NIR) canopy reflectance data. The NRI (Bausch and Duke, 1996) is defined as a ratio of the NIR/green for the target of interest to the mean NIR/green from the reference area. When the mean value of the NRI for the truncated wedge became <0.95, a N application was recommended to the farmer. The target application for each fertigation was 34 kg N ha^{-1}. The farmer fertigated the area between the wedges on the southeast half of the field at his discretion using traditional farmer practices.

A reference area within each major soil type in the field is required to effectively use the NRI. This reference area must not exhibit symptoms of plant N deficiency. Thus, a circular reference strip (Figure 1) 13 m wide was maintained by applying N through an AccuPulse[1] (Valmont Industries, Valley, NE, USA) chemical application system mounted inboard the sixth tower of the center pivot irrigation system. The AccuPulse system consisted of nine heads spaced 1.5 m apart. Nitrogen was applied to the reference strip starting at the V4 (four mature leaves) growth stage (Ritchie *et al.*, 1986) and continued through tasseling (VT). The reference strip also received additional N whenever one of the wedges and/or field was fertigated. Approximately, 400 kg N ha^{-1} was applied to the reference strip during the growing season.

Crop N assessments were obtained with ground-based spectral measurements using an instrumented high-clearance tractor. This system (Figure 2) is described in Bausch and Delgado (2003). Canopy radiance was measured from a nadir view (view angle perpendicular to the crop surface) at 10 m above ground in four discrete spectral wavebands (blue, green, red, and NIR). The viewed circular spot on the ground had a diameter of 2.6 m. Thus, each data point was an integrated value from 25 to 35 plants. As plant height increased, the diameter of the viewed spot decreased due to the fixed radiometer height. Incoming irradiance was simultaneously measured in the same four bands. Data acquisition started around 10:30 a.m. MDT and continued for approximately 2.5 h to traverse transects through the field that covered the truncated wedges. The first data transect was near the pivot road; transect spacing was 24 rows (18 m). Longitude and latitude for each data point was determined with real-time GPS; the GPS antenna was mounted directly above the nadir-view radiometer. Data points were acquired every 2 s when the datalogger was triggered to record data.

Longitude and latitude were associated with each data point in post processing via time matching when measured radiometer voltages were converted to reflectance values based on an inter-calibration of the up- and down-looking radiometers. These data were then imported into ArcView[1] v3.3 to calculate the NRI and to map its spatial variation. Each data point's NIR/green value within wedge A and B for a particular transect was normalized using the mean NIR/green value from the reference strip in the appropriate soil series for the respective transect. Inverse distance weighted interpolation was used to create a surface map (search radius = 20 m, power = 2) with 1 m pixels. Zonal statistics on the NRI (mean, standard deviation, minimum, maximum) and percent area that was N deficient (NRI < 0.95) for each truncated wedge were calculated.

Grain yields were obtained with a combine equipped with a yield monitor and GPS. The farmer provided this information.

Figure 2. High clearance tractor instrumented with radiometers and GPS for georeferenced crop canopy spectral measurements.

Results and discussion

Bausch and Delgado (2003) presented and discussed in-season N application results from a 2-year study pertinent to wedge B that included the 2001-growing season. Their study investigated the use of ground-based remote sensing and the NRI to improve in-season N management for a very sandy low producing area in the field. In the present study, two areas of the field were examined, which had significantly different amounts of residual NO_3-N within the soil profile, to determine what impact such differences in residual NO_3-N had on crop N requirements as assessed using ground-based remote sensing and on in-season N applications. Figure 3 depicts the mean NO_3-N profiles with 95% confidence intervals for the five sample locations from within each truncated wedge (A and B) for the spring soil sampling. Residual soil NO_3-N in wedge A (184 kg N ha^{-1}) was significantly greater ($P < 0.0001$) than that in wedge B (13 kg N ha^{-1}) within the top 1.5 m of the soil

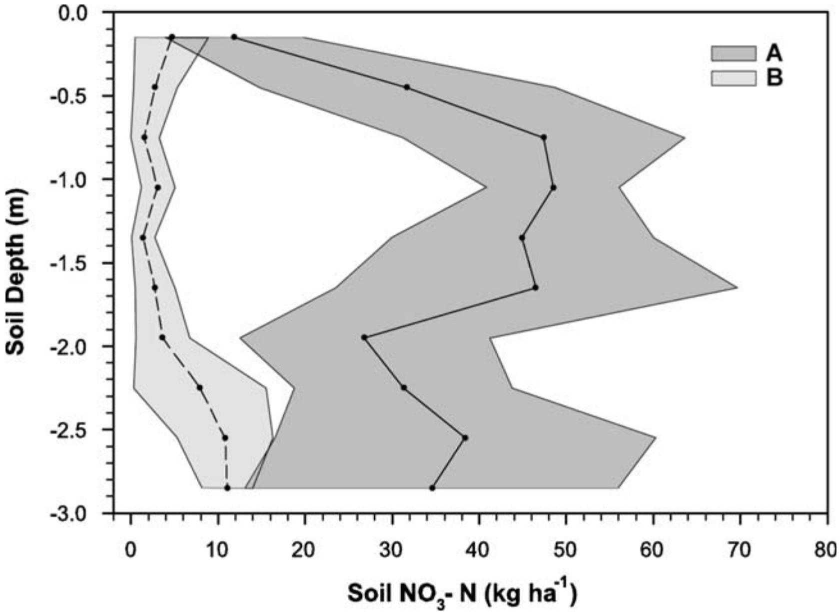

Figure 3. Mean residual soil NO_3-N profiles with 95% confidence intervals for wedge A (solid line) and wedge B (dashed line) obtained in the spring before N fertilizer application.

profile (crop root zone). Thus, considerable differences in potential available soil N existed between the two areas of the field.

The time between growth stage V8 and VT represents the corn growth period accepted by farmers in this geographic area for in-season fertigations. The farmer fertigated the southeast portion of the field between the wedges for the first time on 2 July, i.e., Day of Year (DOY) 183. On DOY 184, corn within wedge A had a mean NRI value of 1.05 (Figure 4 solid line, circle symbols) with 13% of the wedge area designated as N deficient (NRI < 0.95) whereas wedge B had a mean NRI value of 1.03 (Figure 4 dashed line, square symbols) with 26% of the area showing signs of N deficiency. Corn was in its V8 growth stage. When NRI values are above one, the soil background may confuse the index. Schleicher *et al.* (2003) presented a screening technique, based solely on remote sensed measurements, to determine if adequate vegetative cover exited for accurate plant N status classification with the NRI calculated from nadir view data. Using this filtering technique, sufficient green biomass was not present on DOY 184. However, on DOY 191 (V10 growth stage), the screening technique indicated adequate vegetation cover for accurate N status classification; mean NRI values for wedge A and B were 0.99 and 0.98, respectively. The NRI map generated from DOY 194 data showed wedge B with increased N deficiency (mean NRI = 0.93 and 62% of wedge area as N deficient). As discussed by Bausch and Delgado (2003), the northeast portion of the field was hit by a hailstorm on the night of DOY 191 that partially ripped the upper leaves of the corn canopy. Consequently, data taken on DOY 194 (V11 growth stage) was influenced by desiccated leaf tissue along the torn areas in the upper leaves of the canopy. The corn

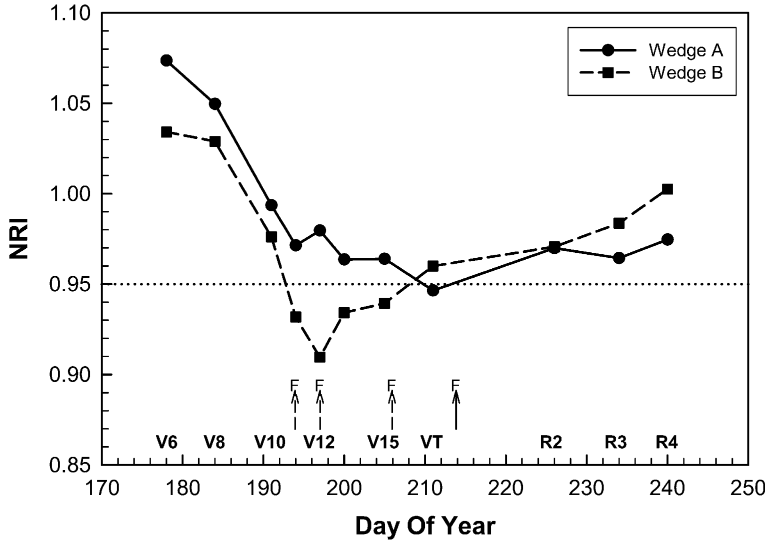

Figure 4. Temporal plot of mean N Reflectance Index (NRI) values and occurrence of fertigations (arrows) for wedge A (solid line) and wedge B (dashed line).

plants were also in their rapid growth period at this time. Wedge B was fertigated (represented by a dashed arrow in Figure 4) with 34 kg N ha^{-1} on the evening of DOY 194 when the sprinkler passed over the area. Two additional fertigations were required for wedge B on DOY 197 and DOY 206 to alleviate N deficiency (Figure 4). At tasseling (VT), the mean NRI for wedge B was 0.96 with less than 40% of its area designated as N deficient. Wedge B received 102 kg N ha^{-1} from these three fertigations. The same in-season N amount was applied in 2000 (Bausch and Delgado, 2003). As shown in Figure 4, wedge B remained in an N sufficient state after VT. Meanwhile, wedge A showed a steady decrease in the mean NRI as the growing season progressed (Figure 4) declining to <0.95 on DOY 211 when the corn crop was at VT. The mean NRI value was 0.946 with 52% of the truncated wedge area designated N deficient. A fertigation was scheduled and occurred on DOY 214 (solid arrow). Due to the lateness in the growing season for this fertigation, the farmer elected to apply 48 kg N ha^{-1} to the wedge area. Wedge A did not require additional N after this fertigation as shown in Figure 4. The field area between the wedges was fertigated five times based on the farmers' management practice. The amounts applied were 67, 34, 34, 34, and 45 kg N ha^{-1} giving a total of 214 kg N ha^{-1}. The farmer's last fertigation occurred on DOY 204 at the V15 growth stage.

Mean grain yields for truncated wedges A and B were 12.6 and 10.8 Mg ha^{-1}, respectively. Grain yield was 12.0 and 10.7 Mg ha^{-1} outside the respective wedges and within comparable areas fertigated by the farmer. Thus, yield was not reduced with reduced N application. Based on the yield obtained, the residual NO_3-N in top 1.2 m of the soil profile (Wiese *et al.*, 1987), the N contribution from the irrigation water applied, the organic matter in the surface 200 mm of soil, and a N recommendation algorithm (Mortvedt *et al.*, 1996), the conventional uniform application of N was calculated to be 82 and 179 kg ha^{-1} for wedges A and B, respectively. Subtracting the combined 34 kg N ha^{-1} applied prior to and at planting left 48 kg N ha^{-1} to be applied in wedge A during the growing season and 145 kg N ha^{-1} in wedge B. These amounts are similar to those applied based on our remote sensing in-season N management technique. Consequently, our results validated the potential use of Mortvedt *et al.* (1996) type algorithms to assess N fertilizer recommendations provided all the information necessary to calculate the N requirement is known *a priori*. However, we suggest using the remote sensing in-season N management technique to further improve N use efficiency because N is applied as needed by the corn crop.

The soil NO_3-N profile at the end of the growing season for wedge B was very similar to the spring profile and not significantly different. Soil NO_3-N in the top 1.5 m of the profile changed from 13 to 16 kg N ha^{-1}. The differences in soil NO_3-N (top 1.5 m) in wedge A between the spring (184 kg NO_3-N ha^{-1}) and fall (54 kg NO_3-N ha^{-1}) sampling times were significantly different ($P < 0.0001$). Because of the high residual soil NO_3-N in wedge A, 166 kg ha^{-1} less N was applied to that area than would normally have been applied by the farmer under his uniform N management practice. For the low residual NO_3-N area (wedge B), we applied 112 kg ha^{-1} less N than the farmer. Unfortunately, the experiment was not repeated during the 2002-growing season to evaluate the potential reduction in N application over consecutive years of site-specific N management because the field was planted to potatoes. Obviously, N savings would decrease in consecutive years due to mining of NO_3-N in the soil profile. Based on results reported by Bausch and Delgado (2003) for wedge B under 2 years of site-specific N management, one could speculate that once the soil/plant system reached equilibrium, the corn crop may require similar amounts of N from year to year. However, this depends a lot on N dynamics of the soil/plant system, i.e., mineralization of organic matter, leaching potential of the soil profile, and N uptake by the particular cultivar of corn grown.

Summary and conclusions

Areas were selected in a commercial corn field that had significant differences in residual soil profile NO_3-N to determine how this affected a ground-based remote sensing N management technique. Wedges were established to facilitate fertigation with the center pivot sprinkler. Monitoring and assessment of plant N in the wedge areas resulted in one in-season N application to wedge A (loamy sand soil) and three N applications to wedge B (fine sand soil) during the growing season. The farmer applied N five times to the field area outside the wedges using his traditional N management practice. In-season N applications totaled 48, 102 and 214 kg ha^{-1}, respectively, for the three areas. Grain yields were 12.6 and 10.8 Mg ha^{-1} for wedge A and B, respectively. Outside the respective wedges and within comparable areas fertigated by the farmer, yields were 12.0 and 10.7 Mg ha^{-1}. Thus, grain yield was not reduced with less N applied to the wedges.

Managing in-season N applications based on remote sensing of the crops' N status reduced N input by 78% in the high residual soil NO_3-N area and 52% in the low residual NO_3-N area compared to the farmer's traditional practice. Soil NO_3-N in wedge A was significantly decreased by 130 kg ha^{-1} in the top 1.5 m of the profile between the spring and fall soil samplings, whereas in wedge B, soil NO_3-N remained relatively constant at <20 kg ha^{-1} in the top 1.5 m of the profile. Consecutive year-on-year site-specific N management may not produce similar N savings due to mining of the residual NO_3-N in the soil profile. However, this will depend on the N dynamics of the soil/plant system.

Remote sensing is one of the new tools available to assess and help to manage the spatial variability of N sources within a field by monitoring the crop N status. Site-specific N management using remotely sensed plant N assessments could minimize over fertilizing in areas with high residual NO_3-N. Applying N fertilizer based on crop "need" may improve N management by decreasing N inputs, decreasing the potential for N leaching, and increasing N use efficiency.

Note

1. Brand names are provided for the benefit of the reader and do not imply endorsement by the authors or the USDA-ARS.

References

Bausch, W. C. and Delgado, J. A. 2003. Ground-based sensing of plant nitrogen status in irrigated corn to improve nitrogen management. In: *Digital Imaging and Spectral Techniques: Applications to Precision Agriculture and Crop Physiology*, edited by T. VanToai, D. Major, M. McDonald, J. Schepers and L. Tarpley (ASA Special Publication 66, ASA, CSSA, SSSA, Madison, WI, USA), pp. 145–157.

Bausch, W. C. and Diker, K. 2001. Innovative remote sensing techniques to increase nitrogen use efficiency of corn. Communications in Soil Science and Plant Analysis **32**(7&8), 1371–1390.

Bausch, W. C. and Duke, H. R. 1996. Remote sensing of plant nitrogen status in corn. Transactions of the ASAE **39**(5), 1869–1875.

Blackmer, T. M., Schepers, J. S., Varvel, G. E. and Walter-Shea, E. A. 1996. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agronomy Journal **88**, 1–5.

Buchleiter, G. W. 1995. Improved irrigation management under center pivots using SCHED. In: *Crop-Water-Simulation Models in Practice*, edited by L. S. Pereira, B. J. van den Broek, P. Kabat and R. G. Allen (Wageningen, The Netherlands), pp. 27–47.

Daughtry, C. S. T., Walthall, C. L., Kim, M. S., Brown de Colstoun, E. and McMurtrey III, J. E. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. Remote Sensing of the Environment **74**, 229–239.

Delgado, J. A. 1999. NLEAP simulation of soil type effects on residual soil NO_3-N in the San Luis Valley and potential use for precision agriculture. In: *Proceedings of the 4th International Conference on Precision Agriculture*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA-CSSA-SSSA, Madison, WI, USA), pp. 1367–1378.

Delgado, J. A. 2001. Use of simulations for evaluation of best management practices on irrigated cropping systems. In: *Modeling Carbon and Nitrogen Dynamics for Soil Management* , edited by M. J. Shaffer, L. Ma and S. Hansen (Lewis Publishers, Boca Raton, FL, USA), pp. 355–381.

Ferguson, R. B., Hergert, G. W., Schepers, J. S., Gotway, C. A., Cahoon, J. E. and Peterson, T. A. 2002. Site-specific nitrogen management of irrigated maize: yield and soil residual nitrate effects. Soil Science Society of America Journal **66**, 544–553.

Fleming, K. L., Westfall, D. G., Wiens, D. W. and Brodahl, M. K. 2000. Evaluating farmer defined management zone maps for variable rate fertilizer application. Precision Agriculture **2**, 201–215.

Gotway, C. A., Ferguson, R. B. and Hergert, G. W. 1996. The effects of mapping scale on variable-rate fertilizer recommendations for corn. In: *Proceedings of the 3rd International Conference on Precision Agriculture*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA-CSSA-SSSA, Madison, WI, USA), pp. 321–330.

Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J. and Dextraze, L. 2002. Integrated narrow-band vegetation indices for prediction of crop chlorophyll content for application to precision agriculture. Remote Sensing of the Environment **81**, 416–426.

Khosla, R., Fleming, K., Delgado, J. A., Shaver, T. M. and Westfall, D. G. 2002. Use of site-specific management zones to improve nitrogen management for precision agriculture. Journal of Soil and Water Conservation **57**, 513–518.

King, B. A., Stark, J. C. and Taberna, J. P. Jr. 1999. In-season spatial variability of potato petiole nitrogen. In: *Proceedings of the 4th International Conference on Precision Agriculture*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA-CSSA-SSSA, Madison, WI, USA), pp. 55–65.

Kostrzewski, M., Waller, P., Guertin, P., Haberland, J., Colaizzi, P., Barnes, E., Thompson, T., Clarke, T., Riley, E. and Choi, C. 2002. Ground-based remote sensing of water and nitrogen stress. Transactions of the ASAE **46**, 29–38.

Mortvedt J. J., Westfall D. G. and Croissant R. L. 1996. Fertilizer suggestions for corn. Colorado State University Cooperative Extension, Service in Action No. 0.538 (Colorado State University, Ft. Collins, CO, USA).

Pierce, F. J. and Nowak, P. 1999. Aspects of precision agriculture. Advances in Agronomy **67**, 1–85.

Ritchie, S. W., Hanaway, J. J. and Benson, G. O. 1986. How a corn plant grows. Iowa State Extension Service Specialty Report 48. (Iowa State University, Ames, IA, USA).

Scharf, P. C., Wiebold, W. L. and Lory, J. A. 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. Agronomy Journal **94**, 435–441.

Schepers, J. S., Blackmer, T. M., Wilhelm, W. W. and Resende, M. 1996. Transmittance and reflectance measurements of corn leaves from plants with different nitrogen and water supply. Journal of Plant Physiology **148**, 523–529.

Schleicher, T. D., Bausch, W. C. and Delgado, J. A. 2003. Low ground cover filtering to improve reliability of the nitrogen reflectance index (NRI) for corn N status classification. Transactions of the ASAE **46**(6), 1701–1711.

Solie, J. B., Stone, M. L., Needham, D. E., Washmon, C. N., Raun, W. R., Johnson, G. V., Lukina, E. V. and Thomason, W. E. 2000. In-season N fertilization using an in-season estimation of potential yield. In: *Proceedings of the 5th International Conference on Precision Agriculture and Other Resource Management*, edited by P. C. Robert, R. H. Rust and W. E. Larson (ASA-CSSA-SSSA, Madison, WI, USA)CD-ROM.

Wiese R. A., Ferguson R. B. and Hergert G. W. 1987. Fertilizer nitrogen best management practices. NebGuide G87–829. (University of Nebraska Cooperative Extension, Lincoln, NE, USA).